Photometric calibration of star fields for the DES

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Abstract

The Dark Energy Survey (DES) is a 5000 deg^2 grizY imaging survey to be conducted using a proposed 3 deg^2 (2. 2-diameter) wide-field mosaic camera on the CTIO Blanco 4-m telescope. The primary scientific goal of the DES is to constrain dark energy cosmological parameters via four complementary methods: galaxy cluster counting, weak lensing, galaxy angular correlations, and Type Ia supernovae, supported by precision photometric redshifts. We present background information on DES, the method for the program that performs photometric calibrations on star fields to be used in the DES nightly calibrations, and the results received from the script.

INTRODUCTION

Background

Early discoveries at the beginning of the twentieth century provided the basis of the leading astronomical research going on today. The astronomer, Edwin Hubble, noted that the more distant a galaxy is, the faster it is moving away from the earth [1]. Ever since, astronomers have generally assumed that the expansion of the universe was slowing down due to the mutual gravitational attraction of its component galaxies. This was the preferred idea until the late 1990s when two teams of astronomers were observing the effects of Type 1a supernovae, and discovered that the velocity of the universe's expansion was increasing with time [2], [3].

The leading theory behind this accelerated expansion is dark energy. It states that there is some energy that cannot be seen that permeates through space causing this acceleration. But in order to fully understand the cosmological principles, dark matter must also be understand. Dark matter is essentially the stuff in space that cannot be seen via electromagnetic radiation, but there is indisputable evidence for its existence. For instance, within the spiral arms of galaxies, the speeds of the objects in the outer arms, according to laws of Kepler, are supposed to have lower velocities than the stars that are closer to the center of the galaxy. However, that is not what is observed. The stars in the outer edge have much higher speeds than the Keplerian predictions, which leads to the proposed idea that there is some unseen mass propelling the speeds of the stars.

These two ideas, dark matter and dark energy, are the two main theories that make up what is known as the Standard Model of Cosmology. The model states that ninety-six percent of what makes up the universe is what cannot be seen directly [10].

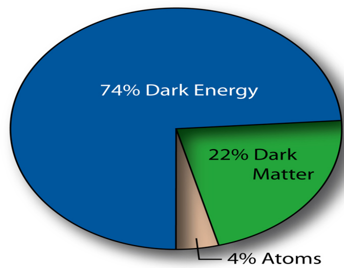

FIG. 1. The Standard Model of Cosmology [10]

The Dark Energy Survey (DES)

The Dark Energy Survey (DES) involves more than 120 scientists from 23 organizations around the world, working together to survey the sky using the Blanco 4-meter telescope at the Cerro Tololo Inter-American Observatory (CTIO) [4],[5]. Over a period of five years, in 525 nights of observing, the survey will catalog the sky in a 5,000 square degree area [5] (roughly 24% of the Southern-hemisphere sky). DES will survey objects to a limiting magnitude of about 24, and a redshift of z $\approx$ 1.5 [6]. DECam, the instrument built to record the data for the DES, is a 570 Megapixel CCD research camera, composed of 74 individual CCDs [5], the DES grizY filters[4], and has a focal-plane-area of 3.1 square degrees [6]. Installation and testing has been completed on the Blanco 4-meter telescope and survey observations begin 31 August, 2013.

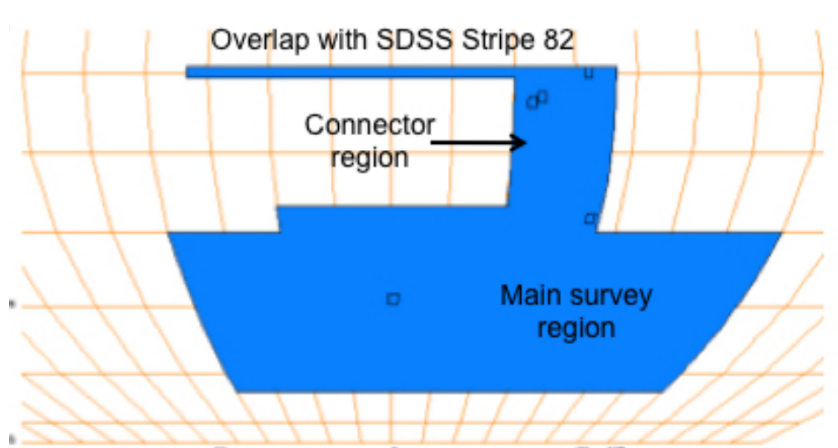

FIG. 2. DES Footprint, credit J. Annis, Fermilab

In order to understand the parameters of dark energy, the DES will be probing it in four different ways that will complement each other in an attempt to constrain the parameters of the dark energy equation-of-state (the ratio of its pressure to its energy density) [7]. The four ways are Type Ia Supernovae, Baryon Acoustic Oscillations, Galaxy Clusters, and Weak Gravitational Lensing.

Type Ia supernovae are being continuously researched because they are what presented astrophysicists with the fact that the expansion of the universe is accelerating. They are studied because they are considered to be the ultimate "standard candle" within the astronomical universe. When this type of supernova occurs, it always has the same intrinsic luminosity, which provides a measure of relative distance via the inverse square law. Also by studying the light given off by the supernovae, the shift in spectra can be inferred, providing the velocity of the expansion of the universe at the time in when supernova occurred. Thus, measuring a large set of supernovae covering a range of distances provides a history of the expansion of the universe, permitting us to measure the expansion rate as a function of time since the Big Bang. The DES plans on capturing approximately 3,000 of these supernovae for study [8].

Secondly, just as Type Ia supernovae provide a standard candle for determining cosmic distances, similar occurrences take place in the distribution of distant galaxies providing a standard ruler through baryon acoustic oscillations (BAO). Shortly after the Big Bang, electrons and protons combined to form neutral hydrogen, freezing acoustic pressure waves that had been created when the universe began to form. By studying the distance that these pressure waves have traveled, the cosmic expansion rate can be found, and thus, be compared to the results from Type Ia supernovae [8].

Thirdly, galaxy cluster counts will be a concentration for the DES. Galaxy clusters are large, gravitationally bound associations of hundreds to thousands of galaxies. Their rate of formation over time is strongly dependent on the amount and properties of dark energy, which tends to counteract gravity. The DES will measure the number of galaxy clusters as a function of time (redshift). It is expected the DES will have a sample of 20,000 measurements [8].

The final probe that the DES will search for will be weak gravitational lensing. This constraint will focus mainly on dark matter. The force of gravity will be used as a detector when light from distant galaxies is bent by large masses. This effect is noticed when the light is focused around dark matter making the galaxy look elongated and distorted. The DES will create a catalog of over 300 million galaxies looking for these distortion affects, which allows for the study of the growth of structure and the expansion over time [8].

Calibrations

But none of the discussed analyses can be completed until the data from the survey have been properly calibrated. A major source of error when it comes to doing astronomy is the earth's atmosphere. The atmosphere can distort images depending on where the telescope is pointed. Furthermore, water vapor and cloud coverage can affect measurements. In order to compensate for this and to achieve photometric calibration, the DES will rely on a set of standard stars. The standard stars are well observed and carefully calibrated. They are placed all across the sky and will be used as a comparison in order to correct for these nightly seeing conditions.

Throughout the process of the survey, four steps of calibration will be performed in order to achieve the desired photometric calibration: Intermediate, Global Relative, Global Absolute, and Final. The intermediate step merely refers to the step of applying the photometric zeropoints and extinction terms measured in nightly absolute calibration to all the observations for a given night. The result is calibrated magnitudes for all the observations on that night [7].

The global relative concerns measuring two tweaks to the calibrated magnitudes from the intermediate calibration step; one of which is a correction to any uncorrected vignetting or scat-tered light effects on the photometry (Star Flat analysis) and the other of which is the calculation of the relative field-to-field (Hex-to-Hex) photometric zeropoint offsets [7].

Next, the global absolute refers to applying the zeropoint adjustments from the global relative calibration step might offset the observed standard star magnitudes from their catalog values. The global absolute calibration step calculates the final overall zeropoints needed—one zeropoint per filter —to place the global relative calibration onto the AB magnitude scale [7].

And lastly, the final calibration step is where the zeropoint adjustments from the global Relative calibration and the global absolute step are applied to the science-filed observations. The output is calibrated AB magnitudes for all the science observations [7].

My work in calibrations

My work entailed writing a program that calibrated the magnitude of stars which is an essential step of intermediate or nightly calibration. My script inputs an SQL query for a certain star field. The query finds all the multiple detections of all the stars in a given star field, as well as the appropriate nightly standard star selection for each detection, and outputs it to a file. A sample query can be found in the appendix. The program separates the file based on the filter for that observation: g, r, i, z, or Y. After that it calls a STILTS[10] command that internally groups the separated files based on RA and DEC to account for multiple observations of the same star, and then sorts them based on whatever group they were assigned. Next the script performs the calculation to obtain the calibrated instrumental magnitude:

$$instru\_mag = mag\_psf + 2.5 * log_{10}(exptime) - zeropoint \tag{1}$$

where mag_psf is the magnitude calculated through SExtractor and is taken from the OBJECTS table; *exptime* is the exposure time in seconds and is taken from the EXPOSURE table; and the *zeropoint* is the instrumental magnitude zeropoint and is taken from the OBJECTS table. The EXPOSURE table contains all the information for a given DES exposure (e.g., telescope position, time of observation, exposure time, filter, etc.). The OBJECTS table contains the measurements of all the detected objects for a given version of the processing of an exposure (e.g., the position and shape of the detexted object and its (uncalibrated) magnitude).

The next step runs through these calibrated magnitudes through a function that does statistical calibration for each star. It runs through each observation of each star based on the GroupID from the matching STILTS command earlier and returns a file based on the grizY filter containing:

- Mean RA and DEC
- Median Calibrated Instrumental Magnitude
- Mean Calibrated Instrumental Magnitude
- Clipped Mean Calibrated Instrumental Magnitude
- Clipped Mean Error for the Magnitudes
- The Number of Observations That Weren't Clipped
- Clipped Sigma for the Magnitudes
- Residuals for the Magnitudes

The next step is that each statistics file outputted by the function are combined based on RA and DEC into one "$All\_Filters$" file. Then this file is matched to the original separated files containing the SQL data so that the following calculations can be equated to achieve a photometric calibrated solution to the magnitude:

$$photometric\_solution = instr\_mag - a - b * (color\_term) - k * X \tag{2}$$

where the $instr\_mag$ is discussed above, the a term is the photometric zeropoint from the PSMFIT table; the b term is instrumental color term coefficient from the PSMFIT table; the k term is the first order extinction coefficient from the PSMFIT table; the X term is the air mass from the EXPOSURE table; and the color term is dependent on what filter the observation was in and is as follows:

- color term g & r = (g-r) - stdcolor0
- color term i & z = (i-z) - stdcolor0
- color term Y = (z-Y) - stdcolor0

The *"color - color" (i.e., g-r)* term is the calibrated color of that star and is the magnitude of the bluer color minus the magnitude of the redder color. For example, the g filter has a transmittance in 475 *nm* range, and the r filter has a transmittance in the 635 *nm* range. The stdcolor0 term is a reference color is take from the PSMFIT table. The PSMFIT table contains the values of the fit parameters from the nightly standard star solution.

Then the function is called again with these newly calibrated magnitudes. It does the same operation as before, and outputs the same statistical parameters with new calibrated magnitudes. Then the outputted statistics files are matched again based on RA and DEC to form a new "*All_Filters*" file. The steps after the previoius "*All_Filters*" file are looped through 3 iterations so that there are 4 outputted "*All_Filters*" and the last one contains the final calibrated magnitudes.

After the calibration is completed, STILTS command-line plotting ability is used. The following plots are outputted:

- As a function of RA and DEC:
  - Clipped Mean
  - Clipped Mean Error
  - Number of Observations Not Clipped
  - Color Terms:
    - g-r
    - r-i
    - i-z
    - z-Y
- g-r *vs* r-i
- r-i *vs* i-z

- i-z *vs* z-Y
- 3d: g-r *vs* r-i *vs* i-z

Star fields

With the data management software that I wrote, I was able to run seven major star fields and calibrate them. They are illustrated as follows:

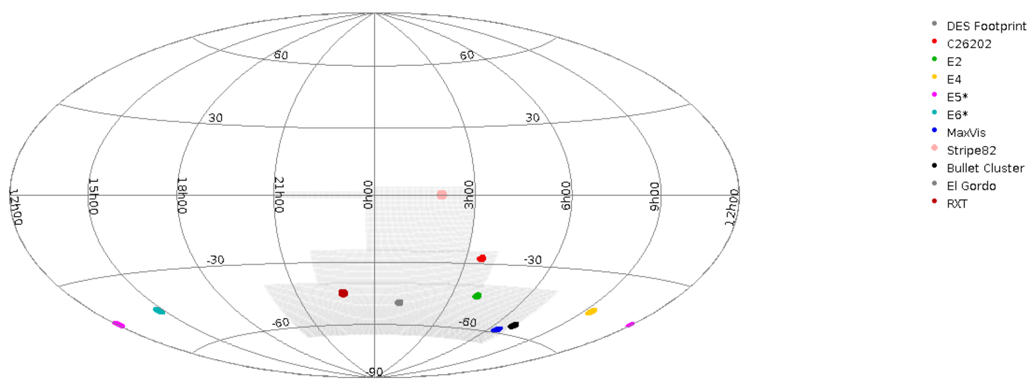

FIG. 3. Calibrated star fields compared to the DES Footprint. They are all in the southern hemisphere, but not all are in the DES Footprint.

These star fields were shot on a night-to-night basis to extract the first order extinction coefficient and the calibrated zeropoints for each star. This is accomplished by applying a linear fit to the air mass *vs*. the instrumental magnitude minus the standard magnitude. By not knowing the standard values for the star magnitudes, these calibration values can not be achieved, and giving reason to why these star fields are shot throughout the night and at different air masses; thus giving me a reason to have these star fields photometrically calibrated. The more accurate mea-surement of the standard star values provides a more precise extraction of the extinction coefficient and zeropoint values.

RESULTS

For each run of the code, I was able to compare the results that I was outputting with currently accepted magnitudes for star fields. Here are graphs comparing the Stripe82 data with the accepted values for that star field.

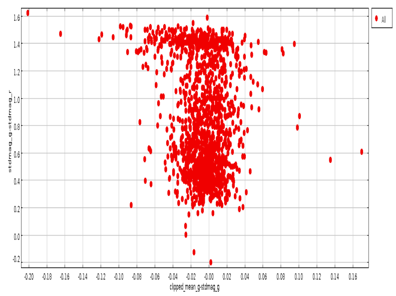

FIG. 4. The outputted magnitudes of Stripe82 stars in the g-band minus those of the Standard star catalog. The y axis is the standard star catalog color index *g*-*r*.

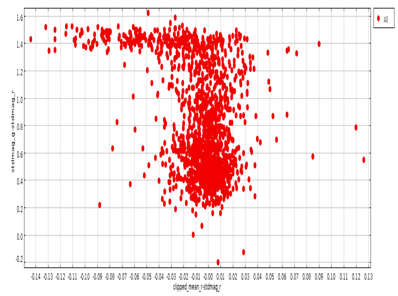

FIG. 5. The outputted magnitudes of Stripe82 stars in the r-band minus those of the Standard star catalog. The y axis is the standard star catalog color index *g*-*r*.

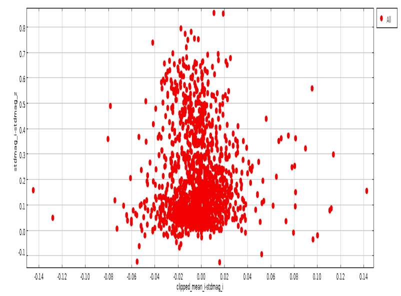

FIG. 6. The outputted magnitudes of Stripe82 stars in the i-band minus those of the Standard star catalog. The y axis is the standard star catalog color index *i*-*z*.

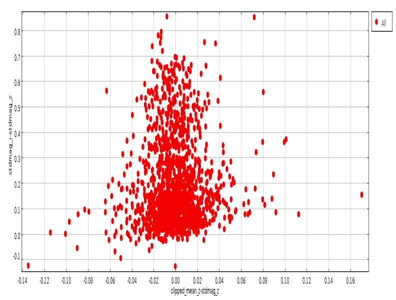

FIG. 7. The outputted magnitudes of Stripe82 stars in the z-band minus those of the standard star catalog. The y axis is the standard star catalog color index *i*-*z*.

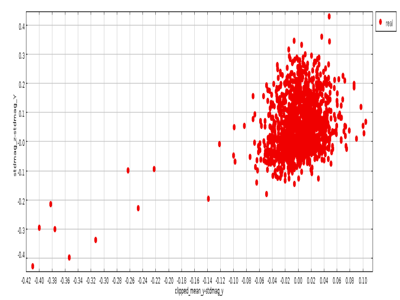

FIG. 8. The outputted magnitudes of Stripe82 stars in the Y-band minus those of the standard star catalog. The y axis is the standard star catalog color index *z*-*Y*.

Each of the graphs above show the magnitude comparisons with accepted standards star magnitudes from the Sloan Digital Sky Survey (SDSS) and with the magnitudes retrieved from the script. This was done as a way to test the script to see if it does its intended job. The difference in the magnitudes are very close to zero (with some outliers) which coincides with calibrated magnitudes being the same as the accepted values.

As well as the clipped magnitudes, the scrip outputs an uncertainty for each star. The uncertainty is calculated as the clipped mean error which is defined as:

$$Clipped\_Mean\_Error = Clipped\_Standard\_Deviation/\sqrt{N\_not\_clipped} \tag{3}$$

Here is a graph of the clipped mean error as a function of RA and DEC:

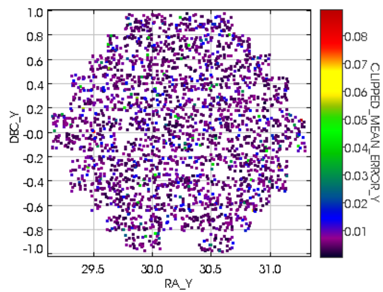

FIG. 9. A graph of Stripe82 star field with the *clipped mean error* as a function of color

The error that is distributed across the field is noticeably in all dark purple which corresponds to below the one percent error bounds. This is consistent for all graphs for this field.

Along with the error graphs, I was to output *color-color* graphs. These graphs are two-dimensional based on color indexes of the stars and can be used to determine what type of stars are in the field. It can give inferences to the spectral type and the temperature of the star. Below are some examples of *color-color* graphs that lie in the Stripe82 field.

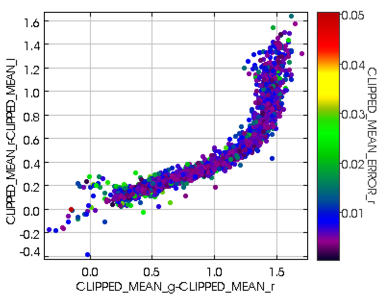

FIG. 10. *Color-Color* graph of *g-r vs r-i* for the Stripe82 star field with the *clipped mean er-ror* as a function of color

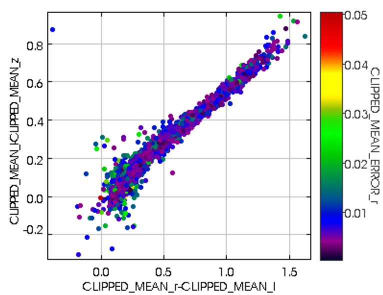

FIG. 11. *Color-Color* graph of *r-i vs i-z* for the Stripe82 star field with the *clipped mean er-ror* as a function of color

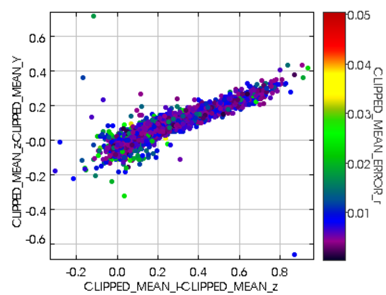

FIG. 12. *Color-Color* graph of *i-z vs z-Y* for the Stripe82 star field with the *clipped mean error* as a function of color

Both axes of the graphs are of colors that are bluer minus those that are redder, which means that the stars that are in the upper right region of the graphs are the bluer stars, which correlates to predominately young, hot stars. The stars that follow the locus to the bottom left are redder stars, which can correlate to old, cool stars.

CONCLUSION

The objective of my research here at Fermilab National Accelerator Laboratory was to develop a method to photometrically calibrate the magnitudes of stars within the standard star fields.

Under the supervision of Douglas Tucker, I developed a script that performs this task. The data reveals that an overwhelming proportion of the stars only deviate from the mean within the error of $\approx 1\%$. When compared to the accepted values from the SDSS standard star magnitudes, the values correspond within the error of ± 0.018 for the g filter, ± 0.018 for the r filter, ± 0.015 for the i filter, ± 0.016 for the z filter, and ± 0.023 for Y filter. The script has been written so that it can be easily adapted to calibrate more star field queries in the future.

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Sample SQL query: Stripe82

```
SELECT
e.id as exposureid, o.imageid, o.object_id, o.x_image, o.y_image, o.ra,
o.dec, o.mag_psf, o.magerr_psf, o.zeropoint, o.zeropointid,
3600.*o.fwhm_world as fwhm_arcsec, o.spread_model, o.flags, e.nite, i.run,
e.propid, e.object, e.band, i.ccd, e.airmass, e.mjd_obs, e.exptime, e.photflag,
i.skybrite, i.skysigma, i.elliptic as image_ellipt, 0.27*i.fwhm as
image_fwhm_arcsec, i.saturate as image_sat_level, i.imagetype, p.*
FROM
exposure e join image i on i.exposureid=e.id join Y1C1_FINALCUT_PRERELEASE
o on o.imageid=i.id left join psmfit p ON (p.run=i.run AND p.filter=i.band
and p.ccdid=i.ccd)
WHERE
(o.ra between 25 and 35) AND (o.dec between -2 and 2) AND (e.object like
'%SDSSJ0200%' or e.object like'%Stripe82Marriner%') AND (e.camshut='Open')
and (e.telstat='Track') AND o.flags=0 AND (o.spread_model between -0.002
and 0.002) AND ( (o.mag_psf - (o.zeropoint-25.0) + 2.5*log(10,e.exptime))
between 13.0 and 21.0 )
```

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